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U. S. NAVAL PROVING GROUND
DAHLGREN, VIRGINIA

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NPG Report No.1125

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U. S. NAVAL PROVING GROUND
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DAHLGREN, VIRGINIA

The Dependence of Limit Velocity on Plate Thickness and Obliquity at High Obliquity

By

A. V. Hershey
Computation and Ballistics Department

NPG REPORT NO. 1125
Task Assignment No. NPG K-11011-1
Date: 23 May 1955

APPROVED: J. F. BYRNE
Captain, USN
Commander, Naval Proving Ground

E. A. RUCKNER
Captain, USN
Ordnance Officer
By direction

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CONTENTS

ABSTRACT

The large number of ballistic data for common projectiles at high obliquity and the large number of ballistic data for monobloc projectiles at low obliquity have been combined, with the aid of corrections for scale, ogive, windshield and hood, to obtain new functions which best represent the fundamental relationship between limit velocity, plate thickness, and obliquity at high obliquity. Functions for the whole range of plate thickness and obliquity have been found specifically for 3" AP M79 projectiles against ductile Class B Armor or STS of $115000(\text{lb})/(\text{in})^2$ tensile strength at $15°C$.

FOREWORD

The material in this report has been prepared since World War II in connection with a study of the mechanism of penetration of plate by projectiles. The report is one of a series of reports. Five of the reports were published at the end of the war, and it was originally planned that nine reports would be submitted altogether. The remaining four reports were held up pending a revaluation of the ballistic data, inasmuch as there was an opportunity to obtain a few additional tests of special interest at the end of the war. As a result of these tests, the number of reports has been increased to eleven. The six remaining reports are now to be published, but with a minimum expenditure of additional effort in order to bring forth the existing material. The analysis has probably been carried as far as it should be carried without the aid of a modern calculator such as the Aiken Dahlgren Electronic Calculator. The press of urgent work has thus far prevented allocation of any ADEC time to this work.

The titles of the full set of eleven reports are as follows:

(1) ANALYTICAL SUMMARY. PART I. THE PHYSICAL PROPERTIES OF STS UNDER TRIAXIAL STRESS. NPG REPORT NO. 6-46

Object: To summarize the available data on the physical properties of Class B Armor and STS under triaxial stress.

(2) ANALYTICAL SUMMARY. PART II. ELASTIC AND PLASTIC UNDULATIONS IN ARMOR PLATE. NPG Report No. 7-46

Object: To analyse the propagation of undulations in armor plate; to summarize previous analytical work and to add new analytical work where required in order to complete the theory for ballistic applications.

(3) ANALYTICAL SUMMARY. PART III. PLASTIC FLOW IN ARMOR PLATE. NPG Report No. 864

Object: To analyse the plastic flow in armor plate adjacent to the point of impact by a projectile.

(4) ANALYTICAL SUMMARY. PART IV. THE THEORY OF ARMOR PENETRATION. NPG Report No. 9-46

Object: To summarize the theory of armor penetration in its present state of development, and to develop theoretical functions which can be used as a guide in the interpretation of ballistic data.

(5) ANALYTICAL SUMMARY. PART V. PLASTIC FLOW IN BARS AND SHELLS. NPG Report No. 954

Object: To analyse the plastic flow in cylindrical bars and shells during impact against an unyielding plate.

(6) ANALYTICAL SUMMARY. PART VI. THE THEORY OF PROJECTILE RICOCHET. NPG Report No. 1041

Object: To analyse the dynamics of projectiles during oblique impact, and to develop theoretical functions which can be used as a guide in the interpretation of ballistic data.

(7) BALLISTIC SUMMARY. PART I. THE DEPENDENCE OF LIMIT VELOCITY ON PLATE THICKNESS AND OBLIQUITY AT LOW OBLIQUITY. NPG Report No. 2-46

<u>Object</u>: To compare the results of ballistic test with the prediction of existing formulae, and with the results of theoretical analysis; to find the mathematical functions which best represent the fundamental relationship between limit velocity, plate thickness, and obliquity at low obliquity.

(8) BALLISTIC SUMMARY. PART II. THE SCALE EFFECT AND THE OGIVE EFFECT. NPG Report No. 4-46

<u>Object</u>: To determine the effect of scale on ballistic performance, and to correlate the projectile nose shape with the results of ballistic test.

(9) BALLISTIC SUMMARY. PART III. THE WINDSHIELD EFFECT, THE HOOD EFFECT, AND THE CAP EFFECT. NPG Report No. 1211

<u>Object</u>: To determine the effect of windshields and hoods or caps on ballistic performance.

(10) BALLISTIC SUMMARY. PART IV. THE DEPENDENCE OF LIMIT VELOCITY ON PLATE THICKNESS AND OBLIQUITY AT HIGH OBLIQUITY. NPG Report No. 1125

<u>Object</u>: To compare the results of ballistic test with the results of theoretical analysis; to find mathematical functions which best represent the fundamental relationship between limit velocity, plate thickness, and obliquity at high obliquity.

(11) BALLISTIC SUMMARY. PART V. THE CONSTRUCTION OF PLATE PENETRATION CHARTS OR TABLES. NPG Report No. 1120

<u>Object</u>: To summarize the results of analysis in the form of standard charts or tables.

The material in this report is basic to the construction of plate penetration charts or tables. It was originally authorized by BUORD ltr NP9/A9(Re3) of 9 January 1943, was later charged to Task Assignment NPG-41-Re3a-118-1 (dynamics of armor penetration), and is currently charged to the Foundational Research Program of the Naval Proving Ground.

The computations for this report were performed by:

V. L. Nichols and J. M. Foster
Mathematical Physics Branch
Computation and Ballistics Department

The analyses and interpretations in this report were conducted by:

A. V. Hershey
Head, Mathematical Physics Branch
Computation and Ballistics Department

This report was reviewed by:

C. C. Bramble
Director of Research
Ordnance Group

INTRODUCTION

Projectile impacts against thin deck plates at high obliquity may occur under long range battle conditions. A large amount of ballistic data for high obliquity have therefore been obtained at the Naval Proving Ground during routine acceptance tests of armor. Very few monobloc projectiles have been used in the tests, and service type projectiles have been used almost universally. Interpretations of the data for both types of projectiles are complicated by rotations of the axes of the projectiles, but the interpretations of the data for service type projectiles are further complicated by the effects of windshields, hoods, and caps. The motion of monobloc projectiles is analysed in reference (1), while the effects of the windshields, and hoods or caps are analysed in reference (2).

The primary variables which enter into the analysis of armor penetration are the mass of the projectile, the diameter of the projectile, the thickness of the plate, the obliquity of impact and the limit velocity. The fundamental relationships between the primary variables are best represented by the terminal ballistics for nondeforming monobloc projectiles in homogeneous plates of constant ductility. In the absence of extensive data for monobloc projectiles at high obliquity, the most likely fundamental relationships between the primary variables have been inferred from the ballistic data for common projectiles with the aid of corrections for the effects of scale, the windshield, and the hood.

The purpose of this work was to compare the results of ballistic test with the results of theoretical analysis; to find mathematical functions which best represent the fundamental relationship between limit velocity, plate thickness, and obliquity at high obliquity.

THE BALLISTIC PARAMETERS

The results of ballistic test may conveniently be summarized in terms of ballistic parameters. The plate penetration coefficient $F(e/d, \theta)$ and the limit energy function $U(e/d, \theta)$ are defined in terms of the projectile mass m, the projectile diameter d, the plate thickness e, the obliquity θ, and the limit velocity v_L by the equations

$$F(\frac{e}{d}, \theta) = \frac{m^{\frac{1}{2}} v_L \cos\theta}{e^{\frac{1}{2}} d}$$

$$U(\frac{e}{d}, \theta) = (\frac{e}{d}) F^2(\frac{e}{d}, \theta) = \frac{m v_L^2 \cos^2\theta}{d^3}$$

The whole mass of the projectile is used in the functions. The projectile mass is expressed in (lb), the projectile diameter is expressed in (ft), the plate thickness in (ft), and the limit velocity in (ft)/(sec).

THEORETICAL FUNCTIONS

A semiquantitative theory of projectile ricochet in armor plate is given in reference (1). The mechanism of a limit impact at high obliquity can be divided into three stages.

(i) and (ii). At the beginning of the first stage of the penetration, an ogival projectile makes a shallow depression in a plate. The rim of the depression spreads out initially at a greater velocity than the velocity of propagation of an undulation in the plate, but eventually an undulation detaches itself from the surface of the projectile. When the projectile has moved a nearly constant distance into the plate, a crack starts and the motion of the undulation is momentarily arrested.

The axis of the projectile is rotated from its original orientation and the nose of the projectile is displaced from its original line of flight. The base continues with little deviation from its original line of flight. The projectile loses contact with the plate just forward of the bourrelet, but renews contact with the plate just forward of the base. The projectile eventually turns into a position with the base through the plate.

The analysis of force and torque during the first two stages of the penetration is based on the following simplifying assumptions.

(a) It is assumed that the force and torque on the nose of the projectile are constant, and are equal to the force and torque on the nose of a projectile whose axis is flush with the plate.

(b) It is assumed that the force and torque on the base of the projectile are constant after the base reaches the plate, and are equal to the force and torque on the base of a projectile whose axis is flush with the plate.

(c) It is assumed that the displacement of the undulation is the same as the displacement in an elastic undulation with the force concentrated at a point.

(d) It is assumed that the second stage comes to an end when the ratio of torque to force is essentially the same for the second and third stages.

(iii). During the third stage the projectile seesaws in the plate until it loses its momentum.

The Analysis of force and torque during the third stage is based on the following simplifying assumptions.

(a) It is assumed that the force and torque are given by the limiting functions when the axis of the projectile is nearly perpendicular to the plate.

(b) It is assumed that the displacement of the undulation is stationary.

(c) It is assumed that the third stage comes to an end when the projectile loses contact with the plate.

In the absence of cavitation, the plate penetration coefficient would decrease steadily to a finite limit as the obliquity is increased to 90°. There is, however, a lower critical obliquity above which cavitation begins to occur, and there is an upper critical obliquity above which a complete penetration is impossible.

The theoretical functions are compared with the standard ballistic function in Figure (1). It is assumed in the theory that no energy is required to propagate a crack after it has first appeared. Evidence that this assumption is responsible for the discrepancy between the functions in Figure (1) may possibly be contained in the measurements of reference (4), where the same amount of work was required to open up cracks as to start cracks in charpy notched bars.

EXPERIMENTAL FUNCTIONS

The ballistic data for 3" monobloc projectiles are summarized in Table III. The ballistic data for service projectiles are enumerated in reference (3). The data for the 4" Comm Mk 16-1 projectile appear to be significantly different from the data for other common projectiles. The obliquity at which the plate penetration coefficient of the 4" projectile is a maximum is greater than the obliquity at which the plate penetration coefficients of the other common projectiles are maxima. The deviation of the 4" projectile from the standard is listed in Table I. The discrepancy may possibly be correlated with a deviation of the inertial properties of the 4" Comm Mk 16-1 projectile from standard, as measured by the inertial parameter

$$\frac{m\bar{\lambda}d}{C}$$

in which m is the mass of the body, d is the diameter of the projectile, C is the transverse moment of inertia of the body, and $\bar{\lambda}$ is the average distance from the center of mass to the nose of the body. The distance $\bar{\lambda}$ is given by the equation

$$\bar{\lambda} = \lambda + \frac{\tau}{\pi a^2}$$

in which λ is the distance from the center of mass to the edge of the bourrelet, τ is the volume within the projectile nose contour, and a is the radius of the projectile. Values of the inertial parameter for various projectiles are listed in Table II.

The interpretation of the ballistic data for common projectiles at high obliquity is obscured by uncertainty as to the limiting range of plate thickness within which the hood remains undeformed. The ballistic data are not inconsistent with the assumption that the hood is usually undeformed when e/d is less than 0.1.

Plates have been received from the manufacturers with reported tensile strengths in the range from 96000 $(lb)/(in)^2$ to 159000 $(lb)/(in)^2$, but no correlation could be detected at high obliquity between the plate penetration coefficients for service projectiles and the reported tensile strengths. Plates which were retreated at the Armor and Projectile Laboratory to other tensile strengths did show a correlation between the plate penetration coefficients for monobloc projectiles and the measured tensile strengths.

The experimental functions for monobloc projectiles have been so adjusted as to coincide with the data for 3" AP M79 projectiles at 60° obliquity. The associated functions for common projectiles pass through the uppermost data for 6" Comm Mk 27-7 projectiles. The data for 75° obliquity are illustrated by Figure (2).

The ballistic data at high obliquity are correlated by a limit energy function $U(e/d, \theta)$ which is expressed analytically by the equation

$$U(\frac{e}{d}, \theta) = (\frac{e}{d})\Phi^2\Theta\cos\theta \qquad (1)$$

in which Φ is a function of e/d, and Θ is a function of θ. The function

Φ is the same for low obliquity or high obliquity when e/d at low obliquity is replaced by $(.53)e/d$ at high obliquity.

The limit energy function at intermediate obliquity is a blend of the limit energy functions for low obliquity and high obliquity. The standard experimental function for the 3" AP M79 projectile in the whole range of obliquity is illustrated by Figure (3).

APPENDIX A

TABLE I

Deviation of the ideal plate penetration coefficient for the 4" Comm Mk 16-1 projectile from the ideal plate penetration coefficient for a standard projectile with the same external geometry.

θ	% deviation
≤ 30	0.0
35	0.0
40	-0.5
45	-3.0
50	-4.0
55	-4.0
60	-3.0
65	-0.5
70	+3.0
75	+4.5

TABLE II

Values of the inertial parameter for various projectiles

Projectile	$\frac{m\bar{\lambda}d}{C}$
3" AP M79	2.01
3" AP Expr. Dw 52 (Hemisphere)	2.08
4" Comm Mk 16-1	1.64
5" Comm Mk 38-1	1.89
6" Comm Mk 27-7	1.99

TABLE III

Plate penetration coefficients for 3" monobloc projectiles vs Class B Armor or STS at high obliquity

Projectile	Plate Number	Tensile Strength	θ	$\frac{e}{d}$	$F(\frac{e}{d}, \theta)$
3" Comm Mk 3-7*	7404A	120000	45°	.083	23600±500
3" AP Type A-Cap	"	123000	60.5°	.084	31000±1000
3" AP M79	23115	115000	60°	.164	32100±200
3" AP M79	42024	102000	44°	.370	34700±200
"	"	102000	49°	.372	36100±200
"	"	104000	52.5°	.370	38800±200
3" AP Type A-Cap	55909	117000	45°	.408	35000±500
"	"	117000	50°	.411	37300±1000
3" AP Type A-Cap	56360	123000	45°	.209	29000±1000
3" AP Type A-Cap	60919	122000	52°	.210	34000±1000
"	"	124000	59°	.215	≥34000
3" AP M79	70015	109000	46.5°	.236	28800±200
"	"	108000	54°	.235	32800±400
"	"	110000	61°	.236	37000±600
"	"	118000	45°	.236	30100±200
"	"	118000	53°	.236	33500±700

* Projectile with nose offset.

TABLE III (continued)

Projectile	Plate Number	Tensile Strength	θ	$\frac{e}{d}$	$F(\frac{e}{d}, \theta)$
3" AP M79	83880	122000	45°	.244	31400±500
3" Expr. dw 52 (Hemisphere)	"	"	45°	.244	≥35600
3" Expr. dw 53 (Type A-1 Body)	"	"	45°	.244	≥33800
3" Expr. dw 54 (Type A-1 Body)	83880	122000	45°	.244	≥35300
3" Expr. dw 55 (Type A-1 Cap)	"	"	45°	.244	33500±200
3" Expr. dw 56 (M51B2 Cap)	"	"	45°	.244	31600±1000
3" Expr. dw 57 (Mk 11 Cap)	"	"	45°	.244	31300±1000
3" Expr. dw 58 (3 cal ogive)	"	"	45°	.244	30100±1000
3" Expr. dw 59 (4 cal ogive)	"	"	45°	.244	30100±1000
3" AP M79	125687	107000	60°	.200	32900±300
"	"	118000	45°	.206	29200±500
"	"	118000	60°	.202	34700±300
3" AP M79	140037	125000	45°	.203	30000±400
"	"	125000	52.8°	.203	31200±200
"	"	125000	60°	.203	34600±700

TABLE III (continued)

Projectile	Plate Number	Tensile Strength	θ	$\frac{e}{d}$	$F(\frac{e}{d}, \theta)$
3" AP M79	140037	111000	60.2°	.202	≥33800
3" AP Type A-Cap	161855	119000	44.5°	.263	31500±1000
"	"	119000	60°	.261	37000±500
"	"	119000	59°	.262	37000±1000
3" AP M79	"	119000	60°	.264	≤41300
3" AP Type A-Cap	189679A	105000	45°	.124	32500±1000
3" AP M79	694385	130000	60°	.245	43500±500
3" AP Type A-Cap	B2714-CA5	145000	45°	.130	32500±1000
"	B2688-CA10	145000	44°	.173	33100±400

APPENDIX B

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(1) Analytical Summary Part VI. The Theory of Projectile Ricochet. NPG Report No. 1041

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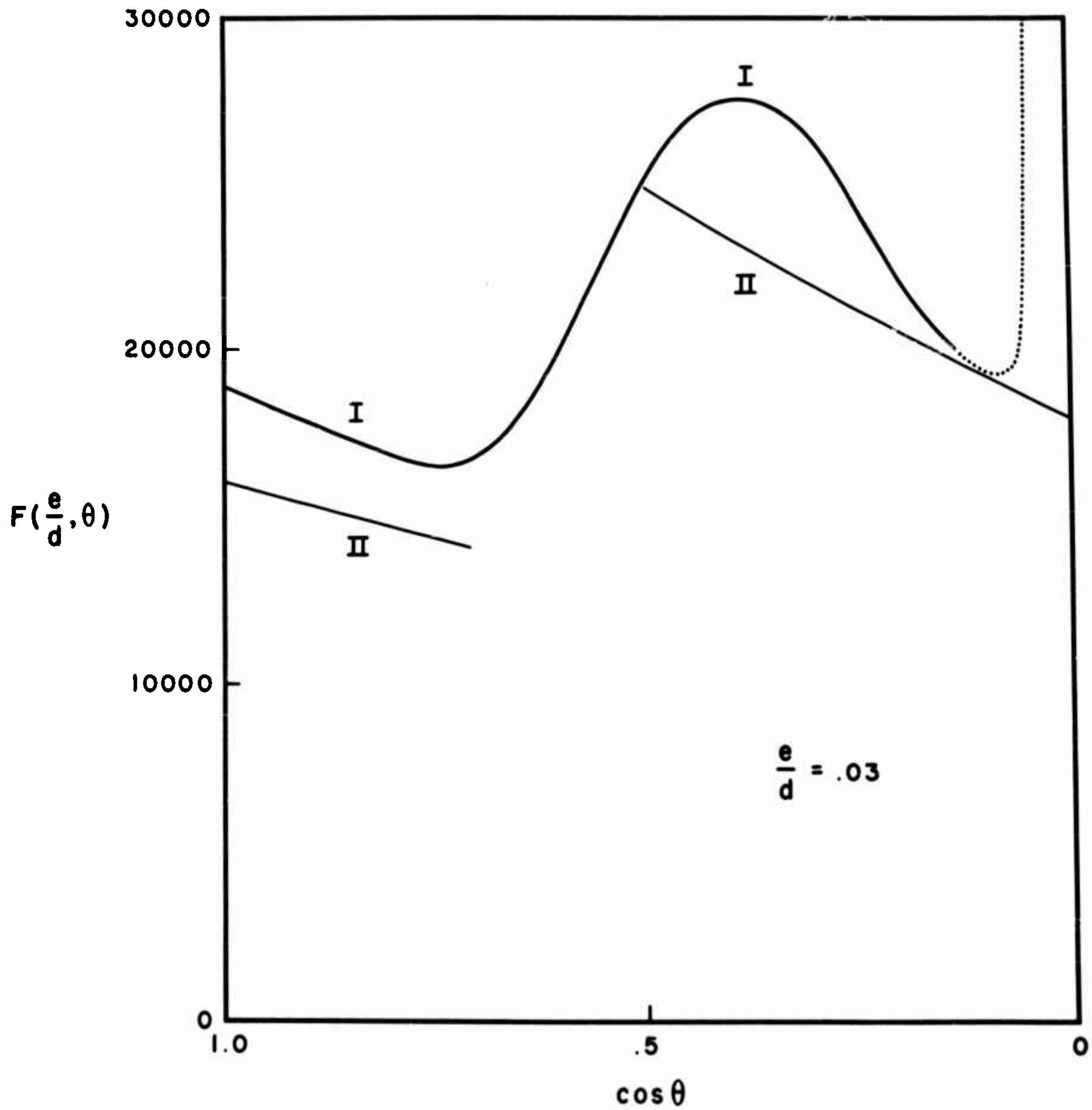
(3) Ballistic Summary Part V. The Construction of Plate Penetration Charts or Tables. NPG Report No. 1120

(4) "Ductility and Fracture Resistance of Ship Plate." A. E. Ruark, I. R. Kramer, P. E. Shearin, et al. NRL Report No. 0-2796 (Nov. 1946)

APPENDIX C

PLATE PENETRATION COEFFICIENTS FOR 3" AP M79 PROJECTILES IN STS



Curve I Standard ballistic function

Curve II Theoretical functions

FIG 1

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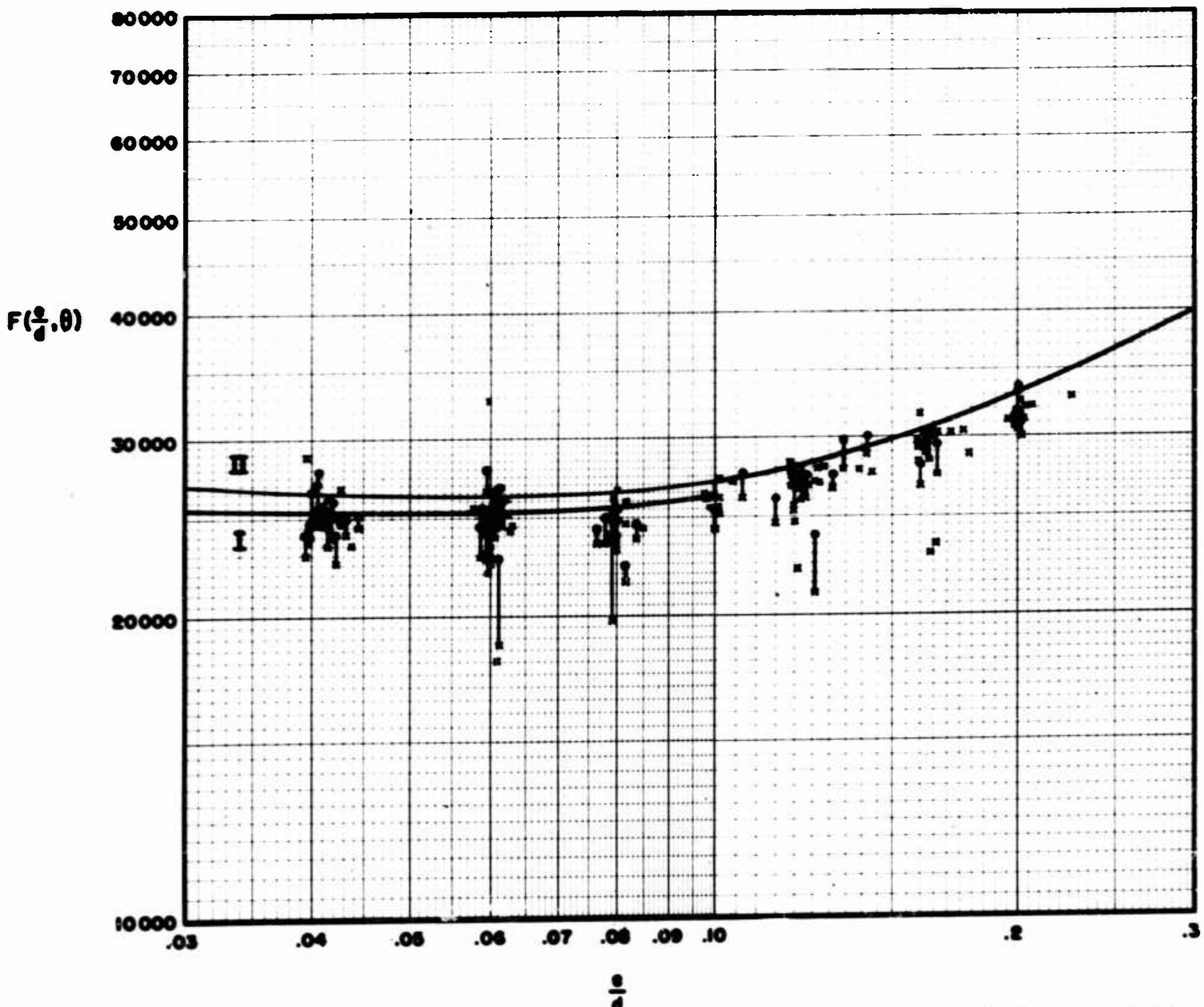
FIGURE (2)

PLATE PENETRATION COEFFICIENTS

6" Comm Mk 27-7 Projectile vs Class B Armor and Special Treatment Steel at 75° Obliquity



x Incomplete Penetration

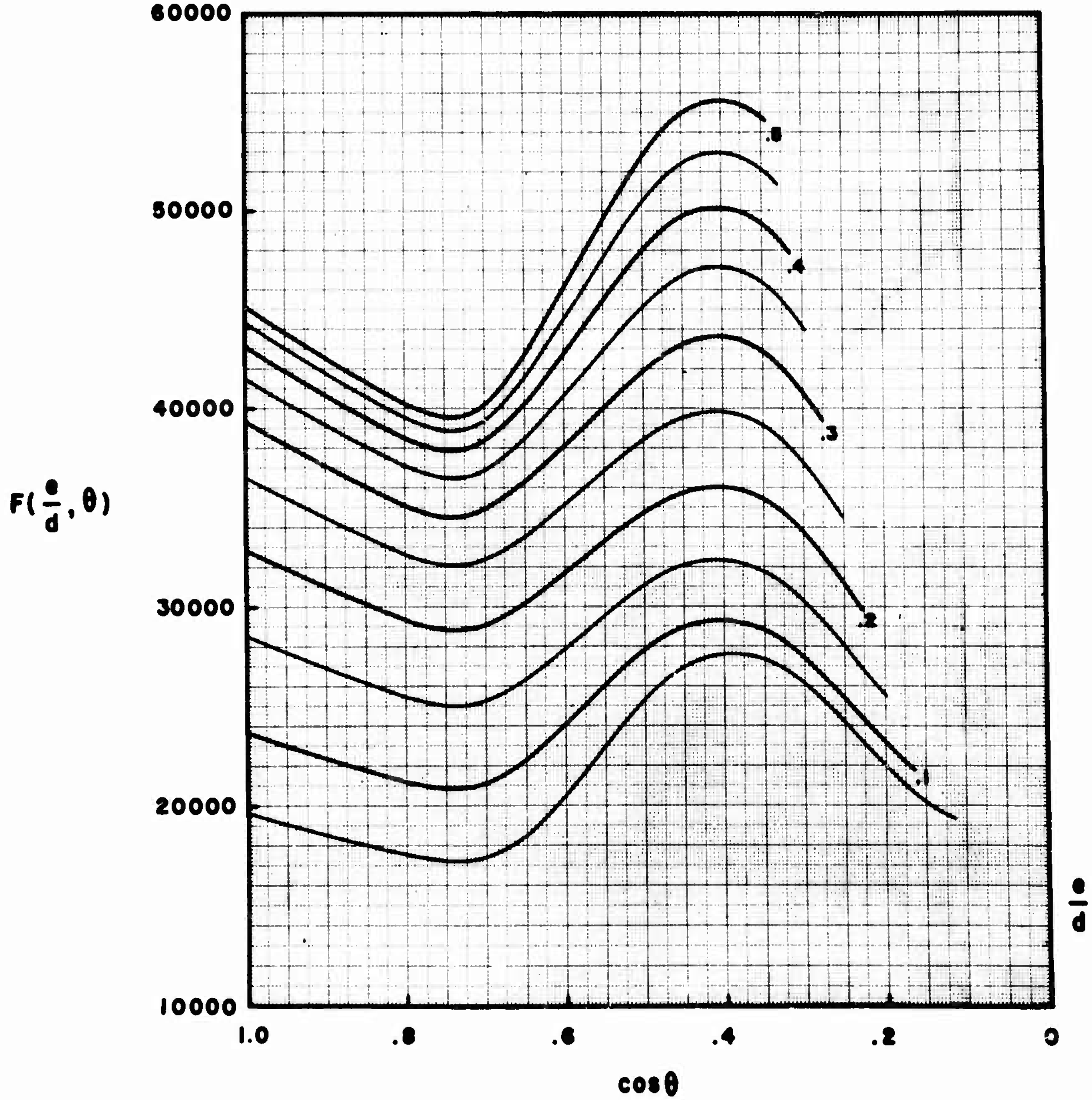
o Complete Penetration

Curve I Nondeforming Hoods

Curve II Deforming Hoods

THE PLATE PENETRATION COEFFICIENT

Standard Experimental Curves for 3" AP M79 Projectile vs STS of 115000 (lb)/(in)^2 Tensile Strength at 15°C



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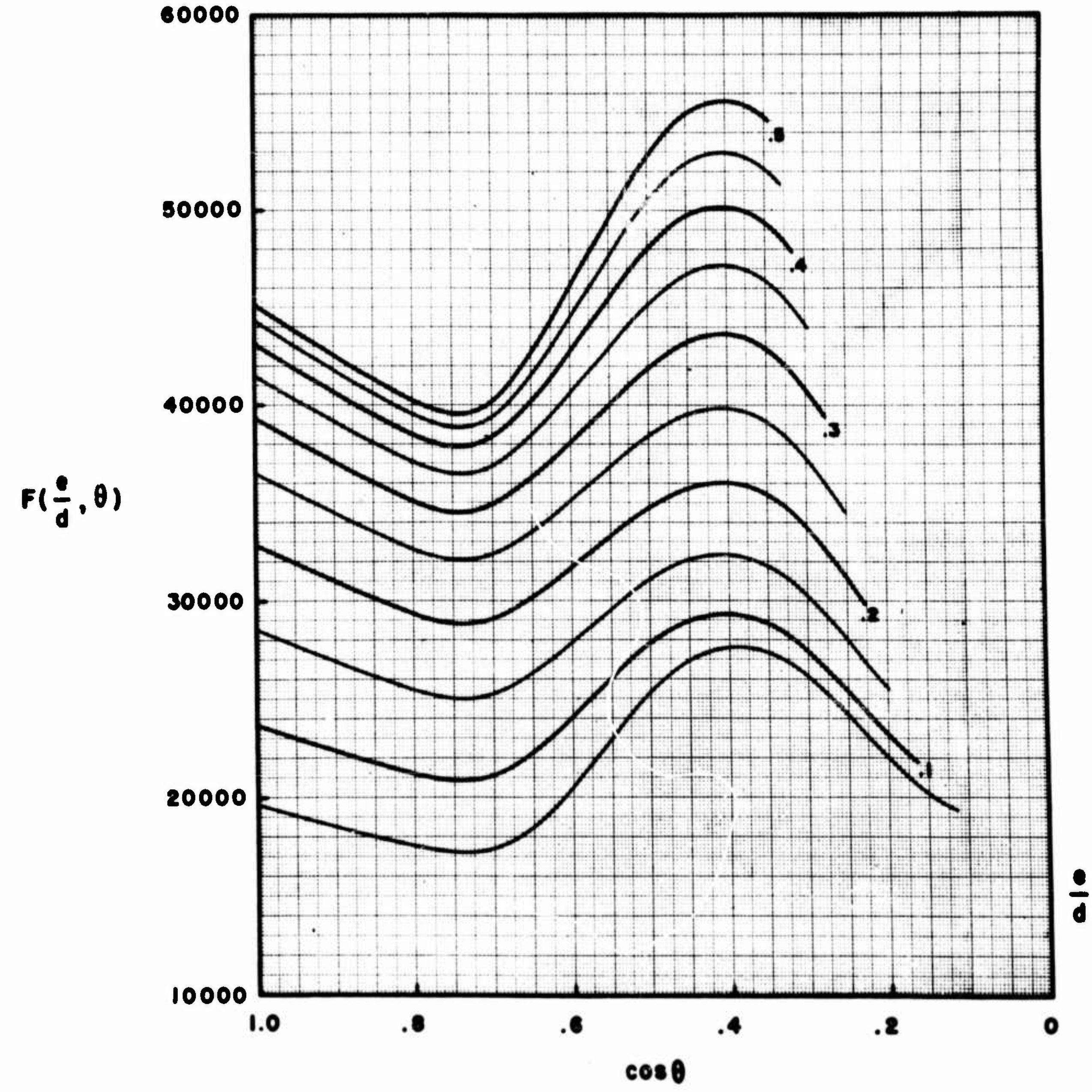
Standard Experimental Curves for 3" AP M79 Projectile vs STS of 115000 (lb)/(in)^2 Tensile Strength at 15°C



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1. Armor plate - Penetration
2. Projectiles - Velocity

I. Hershey, A. V.
II. Title

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